UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL MARINE FISHERIES SERVICE
Northwest Region
7600 Sand Point Way NE
Seattle, Washington 98115

Memorandum

To: Interested Parties

From: NMFS Northwest Region and Northwest Fisheries Science Center

Subject: Guidance Document: Sound Propagation Modeling to Characterize Pile Driving Sounds Relevant to Marine Mammals

Date: January 31, 2012

Objectives: Provide guidance to estimate sound propagation for pile driving sounds relevant to marine mammals.

Scope: This guidance is applicable to pile driving activities in the Northwest Region specifically for use in marine mammal consultations and permit applications, pursuant to the Endangered Species Act (ESA) and the Marine Mammal Protection Act (MMPA). Background information regarding the need for sound propagation estimates is provided below. Where acoustic measurements are intended to inform site-specific sound propagation estimates, data collection methods should take into account spectral, spatial, temporal and sample size considerations, as specified below. Equipment considerations and guidance on data processing are also provided.

Background Information: NOAA is developing comprehensive guidance on sound characteristics likely to cause injury and behavioral disruption in the context of the MMPA, ESA and other statutes. Until formal guidance is available, NMFS uses conservative thresholds of received sound pressure levels from broadband sounds that may cause behavioral disturbance and injury. These conservative thresholds are applied in MMPA permits and Endangered Species Act Section 7 consultations for marine mammals to evaluate the potential for sound effects. Current underwater sound threshold levels for disturbance/injury to marine mammals are: Disturbance: broadband 160 dB_{RMS} re 1µPa for impulse sound (e.g., impact pile driving) and 120 dB_{RMS} re 1µPa for continuous sound (e.g., vibratory pile driving), and Injury: broadband 180dB_{RMS} re 1µPa for cetaceans and 190 dB_{RMS} injury re 1µPa for pinnipeds.

For activities that produce sound above NMFS acoustic thresholds, it will be necessary to evaluate sound propagation from the source and estimate the area(s) within which received sound levels are above the acoustic threshold(s). Propagation of sound in the sea is a complex science. Transmission loss is highly variable in nearshore environments, and hydroacoustic data are needed to accurately estimate spreading and attenuation loss. Spreading loss represents a regular weakening of sound as it spreads from the source, and can be expressed as dB loss per doubling of distance. Spreading loss is a geometric effect that is either spherical or cylindrical. Attenuation loss includes the effects of absorption and scattering, among other effects.

To inform transmission loss estimates, the Northwest Region encourages collection of acoustic data, and review of previous sound propagation studies in the area that may be applicable to the project site. This guidance describes the methodology for collecting and using site-specific data in marine mammal ESA consultations and MMPA permit applications. The Northwest Region generally recommends the use of a practical spreading loss model to estimate transmission loss in the near shore.

Using the practical spreading loss model, transmission loss (TL) in dB units can be defined by:

$TL = 15 \log (R_2/R_1)$

Where R_1 is the distance of a known or measured sound level, and R_2 is the estimated distance that is required for sound to attenuate to a prescribed acoustic threshold.

In practice, this equation can be rearranged to solve for the distance at which sound attenuates to an acoustic threshold:

$R_2 = R_1 * 10\text{^} ((dB_{\text{at } R1} - dB_{\text{acoustic threshold}})/15)$

By mapping the R_2 distance from the project site, a perimeter representing the acoustic threshold can be defined to identify the area of potential sound effects. Land is a barrier to sound transmission. The area of potential sound effects would not extend beyond a distance from the source to land, where land is reached prior to the acoustic threshold.

Knowledge of the background sound in the sea is also important to evaluate whether a sound source is audible over the background level. The Northwest Region and Northwest Fisheries Science Center developed guidelines for collecting background sound data for use in marine mammal consultations and permit applications (NMFS 2011a). Through consultation with NMFS staff, the 120 dB rms threshold may be adjusted if background sound is at or above this level. In the absence of background sound data, NMFS acoustic effect thresholds should be used to define areas of potential sound effects.

Guidance:

Data Collection Methods: The below guidance on data collection methods applies where it is possible to collect acoustic data to inform site-specific sound propagation estimates.

<u>Spectral considerations:</u> For purposes of characterizing sound propagation from pile driving sources relevant to marine mammals, analysis of collected data should eliminate frequencies below the range of functional hearing of marine mammals (described in Southall et al. 2007). The list below identifies common species that occur in nearshore waters of Washington and Oregon by functional hearing group.

Common marine mammal species that occur in nearshore waters of Washington and Oregon:

- Low-frequency cetaceans: humpback, gray and minke whales
- Mid-frequency cetaceans: killer whales (resident and transient)
- High-frequency cetaceans: harbor and Dall's porpoises
- Pinnipeds: Steller and California sea lions, harbor seals, and northern elephant seals

For pile driving, the majority of the acoustic energy is confined to frequencies below 2 kHz (Reinhall and Dahl 2011), whereas above 20 kHz there is very little acoustic energy from either impact or vibratory pile driving (as documented below in Appendix A), and between these two bounds there exists a small but largely negligible contribution. Therefore, 20 kHz provides a robust high frequency limit (f-high) for measuring all pile driving source levels, whereas the low frequency limit (f-low) should be defined by the estimated auditory bandwidth for each functional hearing group (Table 1).

There should be no attenuation in the band between f-low and f-high for the appropriate functional hearing groups listed in Table 1. The roll-off below f-low and above f-high should be as steep as possible and at a rate of at least -40 dB/decade (a decade is a factor of 10 in frequency) after f-low and f-high.

Table 1. F-low and f-high limits for characterizing underwater background sound relevant to marine mammals.

Functional hearing Group[1]	f-low[2]	f-high[3]
Low-frequency cetaceans	7 Hz	20 kHz
Mid-frequency cetaceans	150 Hz	20kHz
High-frequency cetaceans	200 Hz	20 kHz
Pinnipeds	75 Hz	20 kHz

[1] See the above list of common species that occur in nearshore waters of Washington and Oregon, which identifies species to functional hearing groups. All genera represented in each functional hearing group are specified in Southall et al. 2007.
[2] F-low values of estimated auditory bandwidths in Southall et al. 2007.
[3] As documented in the Appendix A below.

<u>Spatial considerations:</u> A far range hydrophone, placed at least 20 times the source depth from the source measurement, should be deployed to provide information on how sound propagates from the source. The location of this hydrophone should be placed appropriately to get a good signal to noise ratio. For example, the hydrophone should not be deployed in a shipping or ferry lane. Additionally, avoid irregular bathymetry between the source and far-range hydrophone location(s). A gradual increase in bathymetry is expected and acceptable, whereas drastic rises or sills between the source and the far range hydrophone are to be avoided. The far-range hydrophone should be placed at depths greater than 5 m, otherwise the precise depth is not critical. These considerations apply to measurements for both impact and vibratory pile driving.

If current velocity ≥ 1.5m/sec occurs at the far-range hydrophone location, flow noise may influence measurements. Best practices to minimize flow noise include deploying the hydrophone at a depth within a few meters of the bottom or use of a flow shield made of latex or spandex that does not trap air, such as the shroud depicted in Figure 1.

Figure 1. Remote hydrophone device with flow shield providing a fluid filled space between shield and hydrophone (photo: J. Laughlin, WSDOT).

Temporal considerations: Measurements need to be collected during active pile driving. Measure the whole pile-driving event, but during data analysis only characterize the periods of maximum hammer energy. Maximum hammer energy is characterized by removing starts (ramp up of hammer energy) and stops (ramp down of hammer energy) from data being analyzed. Also, remove data collected during sound attenuation testing and transition periods associated with sound attenuation. For example, if a bubble curtain is used, remove data between when bubbles are first turned on and after they become fully effective, as well as periods when bubbles are turned off and bubbles have not completely been removed from the water column. Bubbles can remain in the water column after they have been turned off at the source and therefore will interfere with sound production up to ~one minute after the bubble curtain is turned off (Coleman 2011).

Data processing and sample size considerations: Use the far-range measurement (i.e., at least 20 times the depth range) to set the "dB at R_1" variable in the below equation:

$$R_2 = R_1 * 10\text{^} ((dB_{\text{at } R1} - dB_{\text{acoustic threshold}})/15)$$

Use the same data processing protocols for the far-range measurement recommended for source-level measurements, as described below. For each functional hearing group, the far-range measurements need to be reported in overall SPL across the entire frequency band (referred to as "broad band SPL", and defined as the decibel equivalent of the rms pressure within the frequency band, referenced to 1 μPa). Different data processing is required to characterize source levels for vibratory pile driving than for impact driving. For vibratory pile driving, characterize overall dB rms levels by taking 10-second averages across the whole event and averaging all the 10 second periods. Averaging 10 sec periods will likely capture the variation in sound levels over the pile-driving event. For impact pile driving, characterize overall dBrms levels by integrating sound for each waveform across 90% of the acoustic energy in each wave (using the

5-95 percentiles to establish the 90% criterion) and averaging across all waves in the pile-driving event (i.e., as demonstrated in Figure 1 of Madsen et al. 2006). Repeat sampling will help characterize variability.

Equipment considerations: The sensitivity of the hydrophone should be appropriate for the received level to avoid saturation at the 20-times depth range. Additionally, all other equipment considerations for characterizing source levels also apply to far-range measurements (NMFS 2011b). The recording system must be capable of recording the minimum bandwidth required per above frequency considerations. Receiving sensitivities should be sufficient to measure very high acoustic pressures. This device will have different receiving sensitivity than the device used for background sound monitoring.

References

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NMFS. 2011a. Guidance Document: Data Collection Methods to Characterize Underwater Background Sound Relevant to Marine Mammals in Coastal Nearshore Waters and Rivers of Washington and Oregon. Memorandum from NMFS Northwest Region and Northwest Fisheries Science Center to Interested Parties.

NMFS. 2011b. Guidance Document: Data Collection Methods to Characterize Impact and Vibratory Pile Driving Source Levels Relevant to Marine Mammals. Memorandum from NMFS Northwest Region and Northwest Fisheries Science Center to Interested Parties.

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Appendix A.
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Fig. A1 shows the energy spectral density from both impact and vibratory pile driving, integrated over frequency in a cumulative manner and normalized to give a cumulative distribution function (CDF) over frequency. Such a CDF function asymptotes to 1 or 100%, and the plots indicate that the majority of the energy from both impact and vibratory pile driving is confined to frequencies less than about 2 Hz as the CDF is approaching 1 at this frequency. The vibratory pile driving data are from the study conducted at the Port Townsend Ferry terminal in October 2010 (Stockham et al. 2011), and the impact data are from a re-evaluation of results from Reinhall and Dahl (2011); in this case a depth- averaged energy spectral density is used to compute the CDF. It is evident that for both impact and vibratory pile driving that an upper frequency of 20 kHz is entirely sufficient to adequately characterize the frequency distribution.

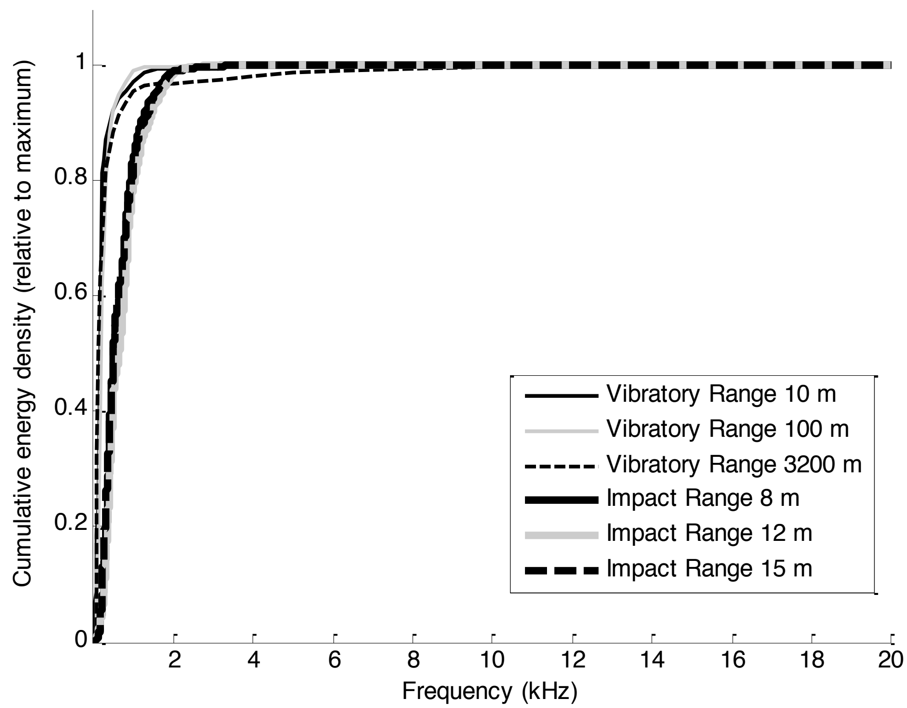

Fig. A1: Cumulative energy relative to maximum based on integration of a energy spectral density for vibratory pile driving from the Port Townsend experiment and impact pile driving from the Vashon Island experiment.

References

Reinhall, P.G., and P. H. Dahl. 2011. Underwater Mach wave radiation from impact pile driving: theory and observation. Journal of the Acoustical Society of America 130: 1209-1216.

Stockham, M.L., P.H. Dahl, and P.G. Reinhall. 2011 Underwater Sound Measurements During Vibratory Pile Driving at Port Townsend, WA.